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Optimization of Collimator Aperture Geometry for BNCT Kartini Research Reactor Using MCNPX

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Boron Neutron Capture Therapy (BNCT) is one of the promising cancer therapy modalities due to its selectivity which only kills the cancer cells and does not damage healthy cells around cancer. In principle, BNCT utilizes the high ionization properties of alpha (^{4}He) and lithium (^{7}Li) particles derived from the reaction between epithermal and boron-10 neutrons (^{10}B + n → ^{7}Li + ^{4}He) in cells, where trace distance of alpha and lithium particles is equivalent with cell diameter. The neutron source used in BNCT can come from a reactor, as a condition for conducting BNCT therapy tests, there are five standard parameters that must be met for a neutron source to be used as a source, and the standards come from IAEA. This research is based on simulation using the MCNPX program which aims to optimize IAEA parameters that have been obtained in previous studies by changing the shape of the collimator geometry from cone shape to cylinder with variations diameter from 3, 5 and 10 cm and also the simulation divided into two schemes namely first moderator Al is placed in a position 9.5 cm behind the collimator and the second is the moderator Al is pressed into the base point of the aperture in the collimator. In this work, neutrons originated from Yogyakarta Kartini research reactor have the energy range in the continuous form. The results of the optimization on each scheme of the collimator are compared with the outputs that have been obtained in previous studies where the aperture of the collimator is in the cone shape. The most optimal output obtained from the results is a collimator with a diameter of 5 cm in the second scheme where the results of IAEA parameters that are producedΦ_{epi} (n/cm^2 s) = 2.18E+8, $\dot{D}_f/\Phi_{epi}$ (Gy-cm^2/n) = 6.69E-13, $\dot{D}_\gamma/\Phi_{epi}$ (Gy-cm^2/n) = 2.44E-13, $\frac{\Phi_{th}}{\Phi_{epi}}$ = 4.03E-01, and J/Φ_{total} = 6.31E-01. These results can still be used for BNCT experiments but need a long irradiation time and when compared to previous studies, the output of the collimator with the diameter of 5 cm is more optimal.

1. INTRODUCTION

Boron Neutron Capture Therapy (BNCT) is one of the promising types of radiotherapy that is used in cancer treatment [1, 2]. This type of radiotherapy utilizes the reaction product that is an alpha particle (^{4}He) and lithium-ion (^{7}Li) that occurs from the fission and nuclear reaction between boron-10 (^{10}B) and thermal neutron (< 0.1 eV). The advantage of BNCT compared to other treatments such as chemotherapy, brachytherapy,

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and etc., is that BNCT can selectively kill the cancer cell without undermining the surrounding healthy cell due to the high LET of the alpha particle 150 keV/μm [3], the other excellence is that the treatment cost and the time for irradiation for BNCT is lower than the conventional therapy [4, 5]. BNCT also is a more economic treatment [6, 7]. There are two important variables in order to make the treatment of BNCT suceed, which is boron concentration in cancer and the neutron flux that is used to bombard cancer. Neutron source for BNCT can come from a nuclear reactor or an accelerator [8]. In the early development of BNCT in 1951 a nuclear reactor were used as radiation source for BNCT but in 2009 an accelerator was developed in order to make the neutron source more compact [9, 10].

Indonesia had been developed BNCT trough an Indonesia BNCT consortium for the past years [11], make use of the 100 kW TRIGA Kartini research reactor as the neutron source for BNCT. This research reactor has six beam port that connects to the reactor core, radial piercing beam port is one of it and has length 312 cm and it is used for BNCT trial and research [11]. Neutron flux in thermal energy from the radial piercing beam port is (6.8 + 0.5) × 10E+7 n cm^{-2} s^{-1}, this neutron flux is needed to be optimized so that BNCT trial for In Vivo and In Vitro can be held in the Kartini research nuclear reactor. The optimization can be done by using a collimator to upgrade the neutron flux and to direct neutron from the reactor. This optimization must at least have to meet the standard that had been established by IAEA that is Φ_{epi}>1.0E+09 (n/cm^2s), $\dot{D_f}/\Phi_{epi}$<2.0E-13 (Gy-cm^2/n), $\dot{D_\gamma}/\Phi_{epi}$<2.0E-13 (Gy-$cm^2$/n), $\frac{\Phi_{th}}{\Phi_{epi}}$<0.05, and J/Φ_{total}> 0.7.

There has been designed and simulations regarding collimator for the BNCT neutron source based on the Kartini research reactor characteristic using MCNPX program [12, 13]. The collimator is 172.5 cm long and in the aperture of it is a cone shape with a diameter 2 cm. The aperture itself has a function to direct the neutron into the cancer target. The collimator consists of five component which are collimator wall composed, moderator, filter, gamma shield, and aperture. The aperture has a function to direct the neutron to the specific target. The results of the simulation with the type of neutron energy in discrete form are Φ_{epi}= 5.03 × 10E+08, $\dot{D_f}/\Phi_{epi}$ = 2.17 × 10E-13, $\dot{D_\gamma}/\Phi_{epi}$ = 1.16 × 10E-13, Φ_{th}/Φ_{epi} = 0.12 and J/Φ_{tot} = 0,835, and the result with the neutron energy in continueous form is Φ_{epi} = 7.57 × 10E+07, $\dot{D_f}/\Phi_{epi}$ = 2.93 × 10E-12, $\dot{D_\gamma}/\Phi_{epi}$ = 7.52 × 10E-13, Φ_{th}/Φ_{epi} = 1.68 dan J/Φ_{tot} = 0.628. This results can still be used for the BNCT treatment [13].

This research aims to find and optimize the five parameters (Φ_{epi}, $\dot{D_f}/\Phi_{epi}$ (Gy-cm^2/n), $\dot{D_\gamma}/\Phi_{epi}$ (Gy-cm^2/n), $\frac{\Phi_{th}}{\Phi_{epi}}$, and J/Φ_{total}) that is obtained from the previous research that have been simulated with MCNPX by change its aperture geometry from cone shape to cylindrical shape with a variance of diameter from 10, 5, and 3 cm, this changing is chosen because of the centrifugal casting tool of the Lampung Mineral Technology Research Institute Indonesian science institute (BPTM LIPI) that is responsible for the collimator casting cannot casting the cone shape of the collimator aperture and also for the In Vivo test [14] the collimator aperture have to be reshape due to the variance of the animal use in the In Vivo test such as rat and pig, the bigger the animal that is used in the test the collimator aperture also have to be bigger. The simulation used neutron energy in the continous form so that the comparison will be about the IAEA five criteria resulting from the collimator with the cone shape and the cylindrical shape. The work was done by simulating the neutron particle transport from the reactor by using the Monte Carlo N-Particle program version MCNPX.

2. METHODOLOGY

The method for this research is computer code simulation based, using devices and program that include a personal computer, Monte Carlo N-Particle (MCNPX) for simulation running, Notepad++ to design the reactor and collimator, Visual Editor Version X 225S use for geometry check, and MS. Excel. The research steps are shown in Figure 1.

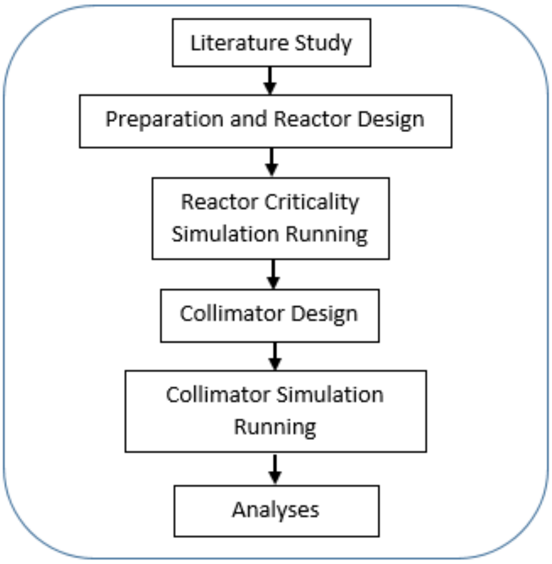
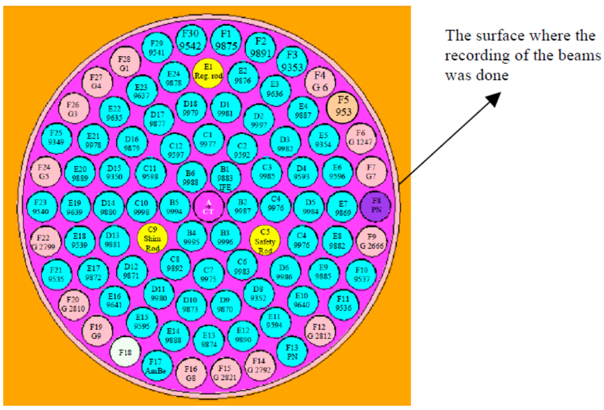
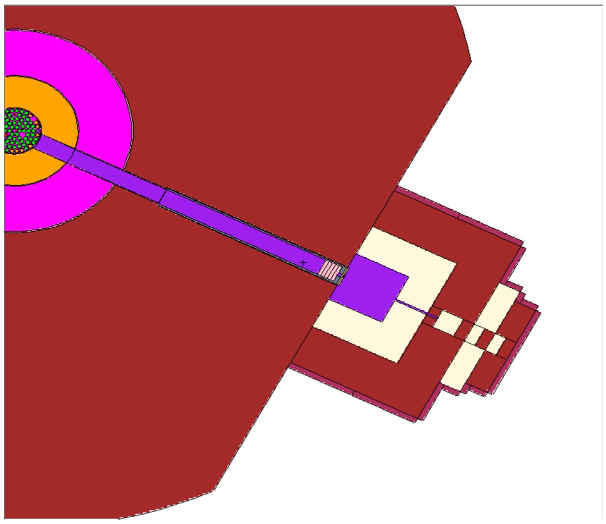


Fig. 1. The research method flow chart

MCNPX can be run into two processes, in this case, the first running done by performing the reactor criticality so that the fission reaction in the reactor core take place and the neutron flux is produced. In this research, the neutron energy is in the continuous form. The neutron flux is produced from the fission reaction then recorded on a surface that is shown in Figure 2. This recorded flux is written in the WSSA file output. The second run is in the collimator where the recorded neutron flux in the WSSA file now called as a source for the second running, with this continuous running the simulation time can be shortened.



(a)



(b)

Fig. 2. (a) Kartini Research Reactor fuel specification and the surface where neutron flux recorded [15]. (b) The display of the reactor and 3 cm collimator by VISED

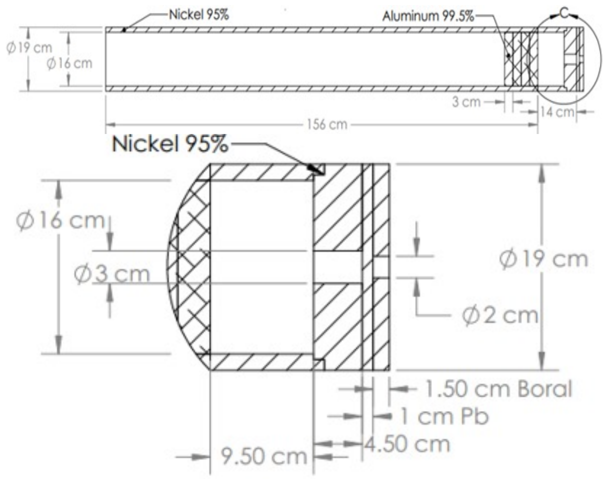


Fig. 3. Geometry detail of the collimator in the cylindrical shape

The collimator shape and material are still the same as the previous design [13] the difference is in the aperture that is used to direct neutron to the specified target, this changing is chosen based on the requirement of the BPTM LIPI Lampung because of their tools cannot yet casting the collimator with the aperture in the cone shape. In this research the shape of the aperture in the cylindrical shape with the length 4.5 cm, shown in Figure. 3. The aperture has a variance of diameter 3, 5, and 10 cm. These diameter are selected for the need of the BNCT In Vivo trial that will be held in the Kartini research reactor, the animal that will be used in the trial is rat, pig, etc so with this type of sample it also need a different type of aperture diameter. The nickel for the collimator wall being used is 95% with the remaining 5% is Mn 1.5%, Fe 1%, Si 0.5%, Cu 1%, C 0.5%, and Ti 0.5%. Al 99.5% is used as a moderator to decrease the neutron energy with the rest 0.5% is Si 0.1%, Fe 0.4%, Cu 0.05%, Mn 0.01%, Ti 0.01%, Ga 0.03%, V 0.01%, Zn 0.05%, B 0.05%. The collimator design divided into two schemes. The first scheme is moderator Al in the position of 9.5 from the aperture by the variance of the collimator aperture diameter 3, 5, and 10 cm. The second scheme is moderator Al tightened to the aperture and also with the variance of the aperture diameter form 3, 5, and 10 cm.

According to IAEA, there are five parameters that have to be met in order to make BNCT treatment can be performed that are Φ_{epi}, $\dot{D}_f/\Phi_{epi}$ (Gy-cm^2/n), $\dot{D}_\gamma/\Phi_{epi}$ (Gy-cm^2/n),$\frac{\Phi_{th}}{\Phi_{epi}}$, and J/Φ_{total} [16]. This research will find these five parameters for each types of the collimator in the scheme 1 and 2.

4. RESULTS AND DISCUSSION

The results of the collimator optimization in a scheme one with the Al position 9.5 cm from the aperture is shown in table 1. It shows that aperture with the diameter 3 and 5 cm is away from the IAEA standard while the aperture with the diameter 10 had a value close to the IAEA for Φ_{epi} 1.21E+08, $\dot{D}_\gamma/\Phi_{epi}$ 8.15E-13 (Gy-cm^2/n), and J/Φ_{total} 6.4E-01. The Φ_{epi} is still can be used for the BNCT trial, the other standard like $\frac{\Phi_{th}}{\Phi_{epi}}$, and $\dot{D}_f/\Phi_{epi}$ (Gy-cm^2/n) are still far from the IAEA standard. The other collimator is still too far from the IAEA standard.

Table 1. The results of the collimator optimization with the moderator Al 9.5 cm from the aperture.

Parameter	Values for Each Type of Collimator Aperture			Value of the Collimator with the Aperture in the Cone Shape	IAEA Recommendation
	10 cm	5 cm	3 cm		
Φ_{epi} (n/cm^2 s)	1.21E+08	8.78E+07	6.98E+07	7.5710E+07	> 1.0E+09
$\dot{D}_f/\Phi_{epi}$ (Gy-cm^2/n)	1.19E-12	1.64E-12	2.06E-12	2.9310E-12	< 2.0E-13
$\dot{D}_\gamma/\Phi_{epi}$ (Gy-cm^2/n)	8.15E-13	1.12E-12	1.41E-12	7.5210E-13	< 2.0E-13
$\frac{\Phi_{th}}{\Phi_{epi}}$	1.17E+00	1.27E+00	1.60E+00	1.68E+00	< 0.05
J/Φ_{total}	6.42E-01	6.36E-01	6.35E-01	6.28E-01	> 0.7

The detail results of the second scheme where the moderator Al is shifted tight to the aperture are shown in table 2. It shows that the value of the five parameters from the IAEA standards that are produced by all the collimator aperture in the cylindrical shape with the diameter 3, 5, and 10 cm is more optimum than the one in the scheme 1 since all the output form the collimator aperture in the scheme one is closer to IAEA standards value, and the one with most optimum value in the scheme one is the collimator aperture with the diameter 5 cm, where the Φ_{epi} 2.18E+8 that is higher than scheme 1 and more, and the $\frac{\Phi_{th}}{\Phi_{epi}}$, and $\dot{D}_f/\Phi_{epi}$ (Gy-cm^2/n) also much optimum than the other collimator in shceme 1 and 2.

Table 2. The results of the collimator optimization with the moderator Al is shifted toward the aperture.

Parameter	Values for Each Type of Collimator Aperture			Value of the Collimator with theAperture in the Cone Shape	IAEA Recommendation
	10 cm	5 cm	3 cm		
Φ_{epi} (n/cm^2 s)	1.20E+08	2.18E+08	7.36E+07	7.571E+07	> 1.0E+09
$\dot{D}_f/\Phi_{epi}$ (Gy-cm^2/n)	1.86E-12	6.69E-13	1.98E-12	2.931E-12	< 2.0E-13

Parameter	Values for Each Type of Collimator Aperture			Value of the Collimator with theAperture in the Cone Shape	IAEA Recommendation
	10 cm	5 cm	3 cm		
$\dot{D_\gamma}/\Phi_{epi}$ (Gy-cm^2/n)	5.45E-13	2.44E-13	7.83E-13	7.521E-13	< 2.0E-13
$\frac{\Phi_{th}}{\Phi_{epi}}$	8.29E-01	4.03E-01	1.26E+00	1.68E+00	< 0.05
J/Φ_{total}	6.61E-01	6.31E-01	6.51E-01	6.28E-01	> 0.7

As neutron interacts with matter, there are three reactions that occur, which are scattering, absorption, and transfer reaction. Scheme 1 shows the neutron flux and gamma dose are too far from the IAEA standard, this happens because many interactions that occur when neutron moderate by Al is the capture reaction, where neutrons are absorbed by the Al and produce more photon that increase the gamma dose from the collimator. From all the schemes, the only collimator aperture that is below the value of the collimator with the aperture in the cone shape is the one that has diameter 3 cm, other apertures produce higher. This happens because the wider the aperture diameter thus the more neutron flux will exit the aperture, results in increasing flux.

The IAEA standard for the thermal neutron flux energy is in the order 1.0E+7 and the epithermal neutron flux 1.0E+9, the chart shows that the aperture with the diameter 10 and 5 cm has a Φ_{epi} is likely close to the IAEA value, this flux is still can be used for the BNCT trial with the treatment time is much longer than the one with the Φ_{epi}> 1.0E+9. This comparison also shows that the neutron flux (Φ_{th}) is in the order 1.0E+8 for the aperture in scheme two with the diameter 5 cm, the Φ_{th} requirement for the BNCT therapy is not high as the Φ_{epi} because it only uses for the cancer that has location in the surface or has a deep in the 3 mm from the surface of the skin.

The dose comparison of the collimator in scheme 2 shows that none of the collimators reach the dose standard of IAEA. The gamma dose from the collimator mainly comes from two source that are the reactor core from the fission reaction as well as the neutron interaction with matter, the addition gamma from the neutron capture reaction increases the gamma dose, therefore, it cannot smaller than the IAEA value. In other parts, the neutron dose is alike gamma dose where none of the collimators approach the IAEA standard. The fast neutron originated from the reactor core is not all moderated by the Al, this occurs due to the purity which is less than 100% based on that neutron energy shifted from fast to epithermal. Since thermal neutron is less than fast neutron, thus fast neutron dose is higher.

In this work, collimator uses cylindrical shape geometry in a variance of diameter with previous studies using cone geometry design for the aperture with a diameter of 2 cm at the end of the collimator is shown in table 1 and 2. All the collimator in cylindrical shape with the diameters of 10 cm in table 1 for scheme one and 10 and 5 cm in table 2 for scheme 2 upgrade the value of the IAEA standard by just changing its geometry from cone to cylindrical shape, this is due to the diameter of the aperture that becomes wider and for that many neutrons just travel straight to the edge of the collimator without colliding by any collimator wall like in the one that uses cone geometry for the aperture.

The results of the collimator with the aperture in the cylindrical shape gives information that for the collimator aperture with diameter 10 cm that is shown in table 1, and the diameter 10 and 5 cm in table 2 are still can be used for the BNCT trial because of its Φ_{epi} still meet the standard of the IAEA due to its order in the range of 1.0E+08 with the consequences ofe irradiation time is longer. For the collimator with the diameter 3 cm on both tables because its output is too far from the IAEA standard it cannot be used for the BNCT trial because of the output is low. Based on that results, it will not kill all the cancer cell. Of all the collimator design in the scheme one and two, the most optimum that is about to reach the IAEA standard is collimator in diameter 5 cm with the Al tightened to the base of the collimator.

5. CONCLUSION

The five IAEA standard parameters resulted from the collimator that is used for BNCT trial with Kartini research reactor as the neutron source can be optimized by changing its aperture geometry. It changes from cone shape to the cylindrical shape, all the five parameters outcome of the cylindrical shape of the collimator aperture with diameter 10 and 5 cm are still match with the IAEA standards by this results BPTM LIPI Lampung can cast the collimator with the aperture in the cylindrical shape that has variance of diameter 3, 5 and 10 cm.

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